Measuring and forecasting of PWV above La Silla, APEX and Paranal Observatories

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ABSTRACT

The content of precipitable water vapor (PWV) in the atmosphere is very important for astronomy in the infrared and radio (sub-millimeter) spectral regions. Therefore, the astrometeorology group has developed different methods to derive this value from measurements and making forecasts using a meteorological model. The goal is use that model to predict the atmospheric conditions and support the scheduling of astronomical observations. At ESO, several means to determine PWV over the observatories have been used, such as IR-radiometers (IRMA), optical and infrared spectrographs as well as estimates using data from GOES-12 satellite. Using all of these remote sensing methods a study undertaken to compare the accuracy of these PWV measurements to the simultaneous in-situ measurements provided by radiosondes. Four dedicated campaigns were conducted during the months of May, July, August and November of 2009 at the La Silla, APEX and Paranal observatory sites. In addition, the astrometeorological group employs the WRF meteorological model with the goal of simulating the state of the atmosphere (every 6 hours) and forecasting the PWV. With these simulations, plus satellite images, radiosonde campaign data can be classified synoptically and at the same time the model can be validated with respect to PWV.

Keywords: precipitable water vapor, atmospheric conditions

1. INTRODUCTION

The European Southern Observatory (ESO), in collaboration with the Institute for Space Imaging Science (ISIS) and the Astrometeorology Group from the Universidad de Valparaíso, conducted a series of dedicated measurement campaigns to characterize the Precipitable Water Vapor (PWV) environment over three observatores in central and northern Chile. Water vapor is the principle source of opacity in infrared and radio (sub-millimeter) spectral regions. These campaigns were performed using an Infrared Radiometer (IRMA)[1], several high-resolution facility spectrograph and series of radiosondes launches. The Astrometeorology group conducted the radiosonde launches over the three observatories.

The first campaign of radiosondes was in May of 2009 at the La Silla Observatory site, located in the Coquimbo region (Figure 1). The second campaign was conducted in July 2009 at the APEX observatory on Llano de Chajnantor, located in Antofagasta region (Figure 1). The third and fourth campaigns, in July/August and then in November of 2009, respectively, were performed in the same region but close to the coast, in Paranal site (Figure 1).

To assist the PWV measurement campaign, the astrometeorology group developed tools to forecast PWV. One of the tools uses an algorithm to extract PWV using GOES-12 satellite images. The other tool is the Weather Research and Forecasting (WRF) meteorological model; this tool can simulate the state of the atmosphere and forecast meteorological variables and conditions. Using this model we can calculate and compare the forecasted of PWV with the value measured by the radiosondes, with the objective of identifying the synoptic patterns, especially those in the PWV.

This study is organized as follow: a brief overview of the instrument used in the radiosonde campaign (section 2), mesoscale model and satellite images (section 3), methodology (section 4), results (section 5) and conclusion (section 6).

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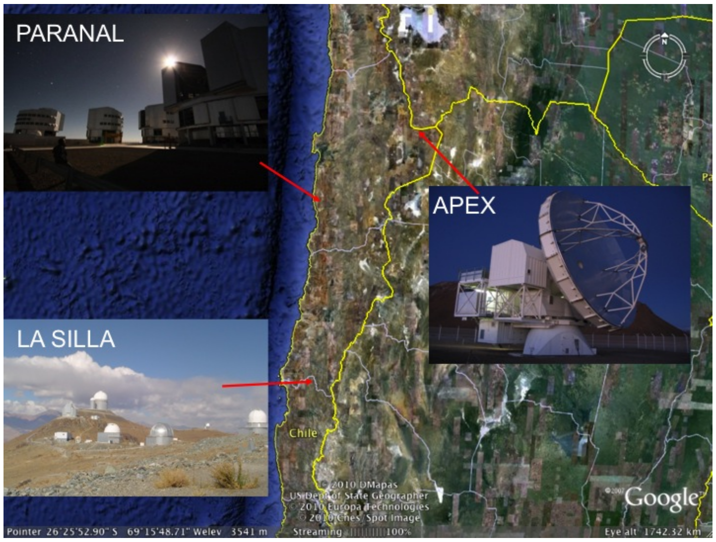

Figure 1. Locations of the astronomical observatories where the radiosondes capaigns were conducted.

2. RADIOSONDES CAMPAIGNS

2.1 Dates of the radiosondes campaigns

The Astrometeorology group team was part of four radiosonde campaigns in 2009. The different duties were: operate the radiosonde equipment, processing meteorological data from each launch and providing data and reports to the rest of the team. These campaigns were dedicated to atmospheric water vapor content measurement above: La Silla, Paranal and APEX observatory. All campaigns launches were authorized and coordinated with Aeronáutica Civil institution.

Table 1. Dates of the radiosonde campaigns at ESO's astronomical observatories in 2009.

ESO Observatory	Dates
La Silla	May 5th to 15th
APEX	July 7th to 16th
Paranal (1)	July 29th to August 10th
Paranal (2)	November 9th to 19th

2.2 Instruments

To measure the vertical profile of the atmosphere above the observatory sites, the astrometeorology group (in a collaboration with ESO) used radiosondes. The equipment employed in the study were:

Vaisala Radiosonde RS92-SGP (Figure 2a): with this type of radiosonde we can measure humidity, pressure, temperature and wind. To collect all of these meteorological data the radiosonde instrumentation package consists of a GPS receiver to track its location, a Silicon pressure sensor, a heated twin humidity sensor and a small Fast temperature sensor.

Ground Check Set GC25 (Figure 2b): used to calibrate and check the functioning of the radiosonde, instrumentation packages, ie. Check the accuracy of the sensor and to set the transmitting frequency of the radiosonde.

Vaisala Sounding Processing Subsystem SPS311 (Figure 2c): a fully digital telemetry link has been implemented between the Vaisala Radiosondes RS92-SGP and the Vaisala Sounding Subsystem SPS311. The radio signal is converted to a fully digital format in the early stages of signal transmission; this improves performance in comparison with conventional analog receivers [2].

Vaisala Portable Antenna Set CG31 (Figure 2d): is a mobile antenna configuration designed for use with GPS wind finding systems in the field conditions. All component are combined using a PC with DigiCORA sounding software. This software connects the Vaisala Sounding Processing Subsystem SPS311 (the Vaisala Portable Antenna Set CG31 is connected to this device) and the Ground Check Set GC25.

The steps we made to launch all the radiosondes is as follows:
1. Unpack the radiosonde.
2. Perform sounding preparation (calibrate the frequency, sensor and telemetry).
3. Prepare/inflate the balloon.
4. Connect the battery.
5. Launch the radiosonde.
6. Monitor the sounding with the DigiCora Sounding System.

The calibrated sensors have the following uncertainties: Temperature is -1.72 & -0.23ºC, Humidity -1.23 & 0.2% and Pressure -5.61 & -3.11 hPa.

Figure 2. Instruments used to perform the campaigns of radiosonde. a) Vaisala Radiosonde RS92-SGP, b) Ground Check Set GC25, c) Vaisala Portable Antenna Set CG31 and d) Vaisala Sounding Processing Subsystem SPS311.

3. THE MESOSCALE MODEL AND SATELLITE IMAGES

3.1 WRF Mesoscale Model

The development of the Weather Research and Forecasting (WRF) modeling system is a multiagency effort intended to provide a next-generation mesoscale forecast model and data assimilation system. The model is being developed as collaboration between the National Center for Atmospheric Research (NCAR), University Corporation for Atmospheric Research (UCAR), Mesoscale and Microscale Meteorology (MMM) Division, between other [3].

This model is a limited-area, non-hydrostatic and terrain following sigma-coordinate. This model can simulated and predict mesoscale atmospheric circulation. The model also has the nesting capabilities (Figure 3).

The boundary conditions used in this model were the FNL model [11] and resolutions used in this study were:

Table 2. Resolution of each domain used in the WRF model.

Domain	**La Silla y Paranal Observatory**	**Apex Observatory**
1	30 Km	27 Km
2	10 Km	9 Km
3	3.3 Km	3 Km
4	1.1 Km	1 Km

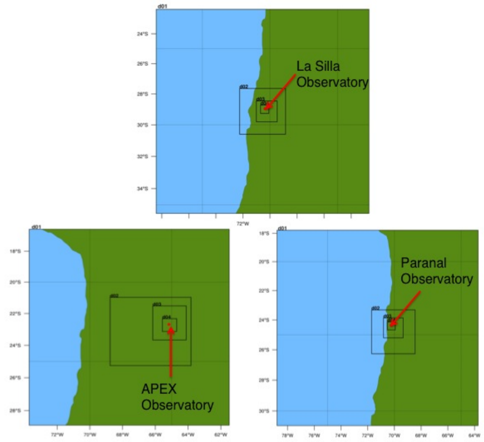

Figure 3. Domains used by the WRF model for each astronomical observatory were the radiosondes campaigns were conducted.

3.2 GOES-12

The GOES -12 (Geostationary Operational Environmental Satellites) is a geostationary satellite, which has a radiometer able to obtain information at different wavelengths, classified into 5 channels. Data from only the third channel (6.5 μm) was kindly provided by ESO. This third channel is located near the center of a strong water absorption band and under clear skies is primarily sensitive to relative humidity averaged over a deep layer centered in the upper troposphere [4]. The methodology used to calculate the PWV using the GOES data is based on studies by Soden & Bretherton [5, 6], Erasmus & Sarazin [7, 8] and Weinreb et al. [9]. PWV is calculated using the following equation:

$$PWV_{goes} = \frac{1}{g}\int_{P_1}^{P_2} UTH\cdot q_{vs}dP \qquad (1)$$

UTH represents the upper tropospheric humidity [8], q_{vs} is the mixing ratio were is calculated using local temperature and local pressure obtained from the radiosonde campaign for each place, dP is the incremental pressure change with height in Pascal and g is the acceleration due to gravity.

4. METHODOLOGY

In order to develop this study the following steps were taken:

1. - Calculated the value of PWV directly from the radiosonde data, using the next equation:

$$\mathrm{PWV} = \frac{1}{g}\int_{P_1}^{P_2} q_{vs}dP \qquad (2)$$

Were q_{vs} is the mixing ratio at a given pressure level, p, then the PWV contained in a layer bounded by pressures p1 and p2 and g is the acceleration of gravity. This equation was used with the data measured by the radiosondes and the values simulated using the WRF mesoscale model.

2. - Calculate the PWV using the data from the satellite images of GOES-12 using the equation (1) for APEX observatory, only.

3. – Extract the vertical profiles of the meteorological values from the WRF model, using a linear interpolation based on each location in the study.

4. – Perform a statistical analysis, correlation analysis (Cor), root mean square error (RMSE) calculation. Determine the bias and cumulative distribution function (CDF).

5. – To classify the synoptic pattern, the study was based on the classification made by Cuevas et al. [10].

5. RESULTS

5.1 Evaluation of PWV Values

The evaluation of the WRF model was performed by comparing data from domain 4 of the model (highest resolution ~1 km) against the data measured by the radiosonde. Then the evaluation of PWV calculated by GOES-12 was, again, compared against the values measured by the radiosondes.

WRF Model

The comparison of PWV values is made using the values of the radiosonde and the values analyzed and forecasted from WRF model. All the values of PWV were calculated using equation (2).

The first PWV campaign was conducted at the La Silla site; Figure 4 shows a time-series comparison of determined PWV values. In this Figure, the values analyzed and forecasted by the WRF model overestimated PWV by more than 2 mm and the 48 hour forecast overestimated PWV by more than 3 mm (Table 3). The 24 hour forecast had the lowest CDF values, where 50% of the data had an error of < 2.3 mm.

Table 3. Statistical parameters between the values of PWV measure by the radiosondes and the forecast from the WRF model.

Statistical Parameters	**Observatory**											
	La Silla			APEX			Paranal (1)			Paranal (2)		
Forecast (hrs)	ana	24	48	ana	24	48	ana	24	48	ana	24	48
Corr	0.91	0.80	0.83	0.93	0.93	0.93	0.83	0.71	0.66	0.48	0.61	0.31
BIAS (mm)	2.72	2.48	2.97	0.13	0.13	0.15	1.47	1.68	1.93	2.43	2.09	2.35
RMSE (mm)	2.92	2.80	3.23	0.56	0.6	0.6	1.66	1.88	2.29	2.53	2.27	2.52

The second PWV campaign was conducted at the APEX Observatory, Figure 5 shows good agreement between values simulated using the WRF model and the data measured by the radiosondes. The correlation between the 24 hrs and 48 hrs forecasts is 0.93. On average, the WRF model simulations overestimated the PWV, but not by < 0.7 mm (Table 3). Rescpect to CDF fuction the 75% of error of the analyzed and forecast data is < 0.58 mm (in average).

The third PWV campaign was conducted at the Paranal site, in the middle of the winter season. Figure 6 shows the PWV analysis and the forecast from WRF model overestimated > 1 mm. The correlation with the analysis data is 0.83 with an RMSE of 1.66 mm (Table 3). As for the CDF function 50% of the data (compared with the PWV analysis) has an error < 1.15 mm and all data has an error <3.12 mm.

The fourth campaign was, again, conducted at Paranal but this time during the warm season month of November. One objective of this last campaign was to get a seasonal comparison of PWV for this site. The performance of the analysis and forecast of PWV by the WRF model are not as good were realized with the third campaign. Figure 7 shows the time series of PWV and, again, the model overestimates the value. The best correlation comes from the forecast of 24 hrs (0.61) also giving the lowest the RMSE (2.09 mm, Table 3). The CDF function says the 50% of the comparison with forecast of 24 hrs has an error of <1.93 mm. This is the lowest value if we compare with the analysis data error and 48 hrs forecast data where this value is closer to 2.4 mm.

As we can see in Figure 4, 6 and 7 the data analyzed and forecasted by the model has an error but they present the same tendency, this is because the place were performed the launchs of the radiosondes are not the same coordinated used on the model. The difference in distance can be between 1 Km (La Silla) and 500 m (Paranal) and in elevation aver 50 m. But in APEX this the launchs were made nest to the antenna, that why the error is more lowest.

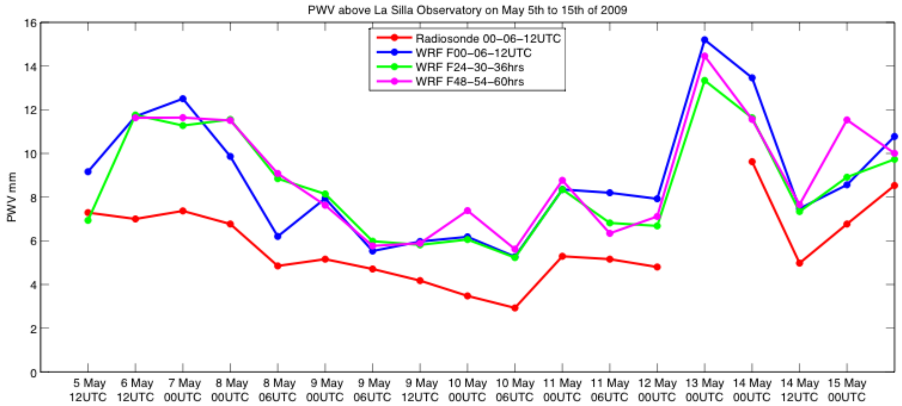

Figure 4. Comparison of PWV measured at the La Silla site by the radiosondes (red line) and the PWV from the WRF model at analysis hrs (blue line), 24 hrs of forecast (green line) and 48 hrs of forecast (magenta line).

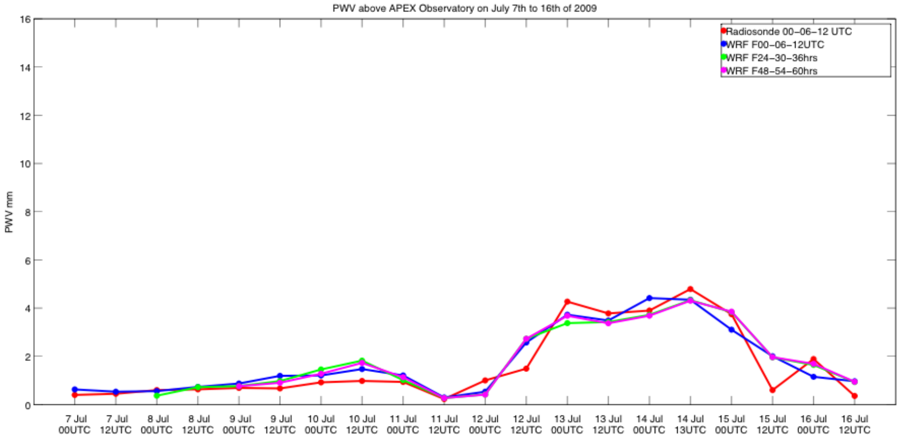

Figure 5. Comparison of PWV measured at the APEX Observatory by the radiosonde (red line) and the PWV from the WRF model at analysis hrs (blue line), 24 hrs of forecast (green line) and 48 hrs of forecast (magenta line).

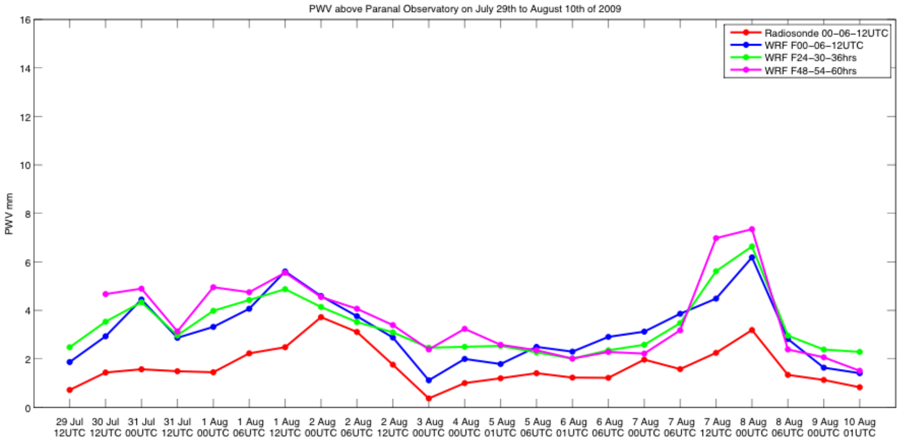

Figure 6. Comparison of PWV measured at the Paranal site (1) by the radiosonde (red line) and the PWV from the WRF model at analysis hrs (blue line), 24 hrs of forecast (green line) and 48 hrs of forecast (magenta line).

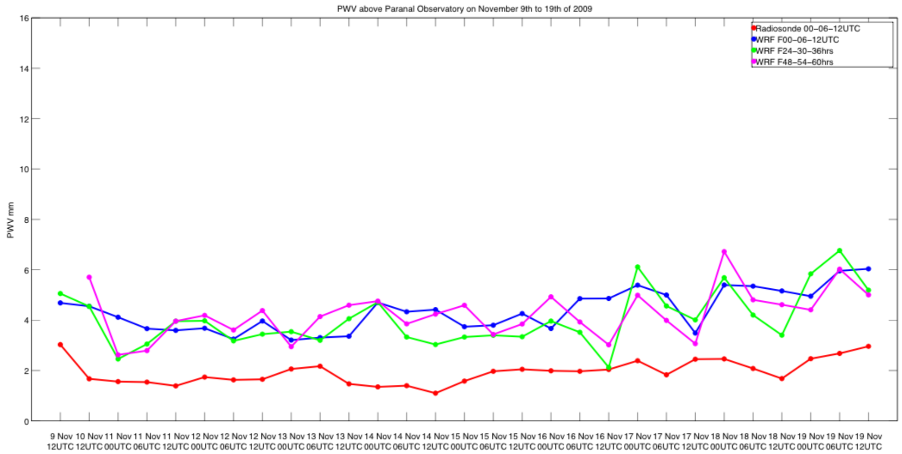

Figure 7. Comparison of PWV measured at the Paranal site (2) by the radiosonde (red line) and the PWV from the WRF model at analysis hrs (blue line), 24 hrs of forecast (green line) and 48 hrs of forecast (magenta line).

GOES-12

In order to calculate the PWV from GOES-12 images is required vertical profile of the saturated mixing ratio (Section 3.1). To calculate this specific profile needs the vertical profiles of temperature, dew point temperature and pressure. As input we used two sources to make these calculations, the radiosonde data and global model data FNL. This methodology is used only in APEX observatory, the next step is going to have the PWV over La Silla and Paranal site.

Table 4. Statistical parameters between the values of PWV measured by the radiosondes and the PWV values calculated from the GOES-12 using the vertical profiles from the radiosondes and FNL model.

Statistical Parameters	**Observatory**	
	APEX	
	FNL	RS
Corr	0.57	-0.10
BIAS (mm)	5.40	-0.77
RMSE (mm)	7.60	1.75

Figure 8 shows the time series of PWV for the APEX observatory where the values of GOES12-FNL overestimated a of BIAS 5.4 mm but the GOES12-RS underestimated the values, giving a BIAS of 0.77 mm (Table 4). The RMSE of GOES12-FNL is four time more bigger than the RMSE of GOES12-RS (table 4) but the correlation on GOES12-FNL is 0.57 as compared with the values of GOES12-RS (-0.1) is the best (Table 4). With respect to the CDF function, the forecast of GOES12-RS has the lowest values compared with the GOES12-FNL, because 50% of the data of GOES12-RS has an error < 0.3 mm and GOES12-FNL has an error < 4.23 mm.

Vertical Profiles

As describes in Section 4, to compare vertical profiles we linearly interpolated the data and computed the average for each campaign, with the objective of providing a simultaneous analysis during the fourth campaign. The simulated profiles included temperature, relative humidity, mixing ratio, wind speed and direction.

The vertical profiles of temperature are similar to the profiles measured by the radiosondes. The error is >1ºC between pressure of 750 hPa and 600 hPa. Between these pressures the model underestimates the temperature values during the first, third and fourth campaigns (La Silla and Paranal). However, at APEX, the model mostly overestimated temperature, but by less than a 1ºC, see Figure 9.

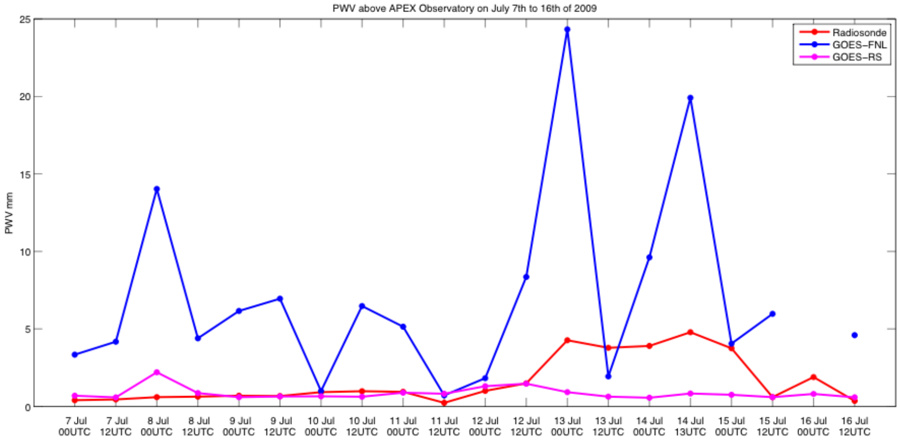

Figure 8. Comparison of PWV measured at APEX Observatory by the radiosonde (red line) and the PWV calculated by GOES-12/FNL (blue line) and PWV calculate by GOES-12/RS (magenta line).

The comparison between the profiles of relative humidity shows that at lower pressures the error is <20% and the third and fourth campaigns have an error <10% (Figure 10). In the upper pressures, the errors increase to more than 30%. This error may be present because the model does not simulate the contribution of upper troposheric humidity carried in by the Subtropical Jet Stream (JS, is a strong wind concentrated in a relatively narrow region in the upper troposphere).

The vertical profiles of the mixing ratio do not have the same values because those measured by the radiosondes are larger than the values simulated by the model. The model tends to underestimate lower PWV values. Figure 11 shows the average of the mixing ratio profile to the fourth campaign of radiosonde.

Respect the vertical profile of the wind speed in the four campaign the average of the vertical profile simulated by the model present the same tendency as the average of the radiosonde. The best simulation of the vertical profile is between APEX site and the second campaing over Paranal site, because the errors are < 2 m/s. The wind direction the model overstimate the values, most of the time, but the big difference between the vertical profiles are in the lows and middle pressure levels.

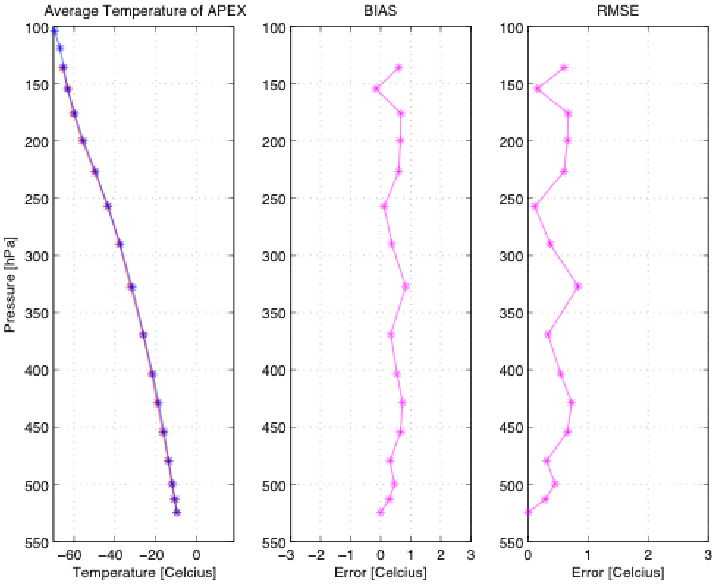

Figure 9. Mean vertical profile of temperature, corresponding to the second campaign of radiosondes (first box), BIAS in the vertical profile (second box) and RMSE of the model with respect to the radiosondes (third box).

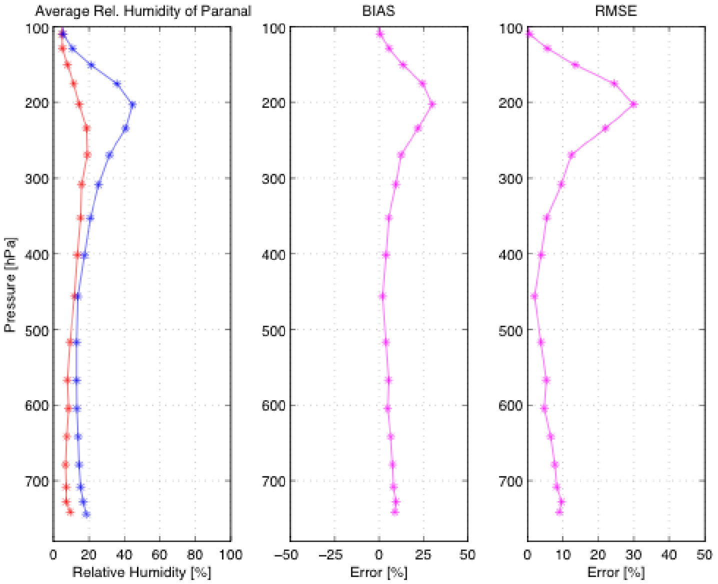

Figure 10. Mean vertical profile of relative humidity, this corresponding to the third campaign of radiosondes (first box), BIAS in the vertical profile (second box) and RMSE of the model with respect to the radiosonde (third box).

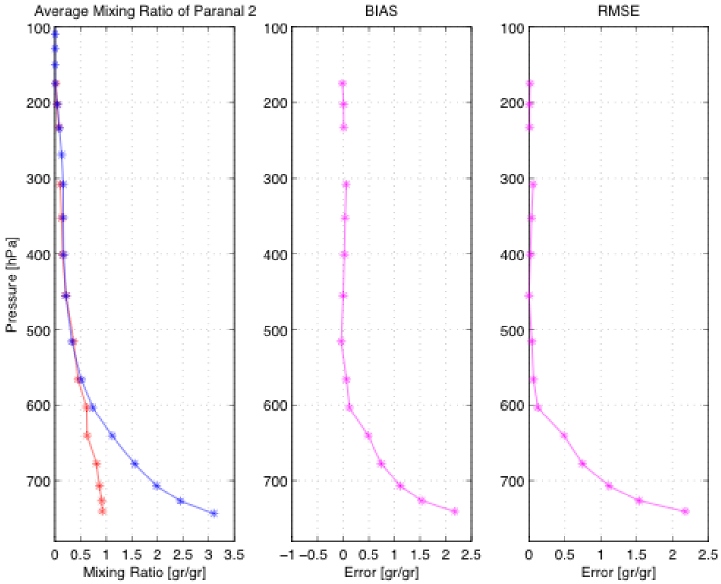

Figure 11. Mean vertical profile of mixing ratio, this corresponding to the fourth campaign of radiosondes (first box), BIAS in the vertical profile (second box) and RMSE of the model with respect to the radiosondes (third box).

5.2 Meteorological study

A meteorological study of the PWV measured by the radiosondes in the four campaigns has been performed. The aim of this study was to identify a relationship between meteorological conditions and PWV. In this study we used different data sets to identify the synoptic conditions in the atmosphere. The data set used to make this study were the local parameters from the weather station at each campaign site, satellite images and the WRF model simulation of domain 1.

This synoptic pattern was based on the study by Cuevas et. al. [9]: Anticyclone Predominance (AP), carrying high pressure related with clear skies and dryness. High Trough (HT) is a wave prolongation of cyclonic circulation, showing up in the mid- and high-troposphere, causing an ascending movement and instability in the front part of the trough and a descending movement in the posterior part of the trough. Altiplanic Winter (AW) is a convective zone over Bolivia (spring and summer season), produced by the Amazon's zone and Inter Tropical Convergency Zone (ITCZ). Cut-off Low (CL) is a cold nucleus corresponding to air that is colder than its surroundings, which, because of circulation, continues turning cyclonicly, forming troughs and fronts at altitude. Jet Stream (JS), is a strong wind concentrated in a relatively narrow area in the upper troposphere.

During the campaign over the La Silla site, PWV was always >2.5 mm. The campaign was carried out in May. This month is known to be characteristically very cold and very unstable because is in the last part of autumn season. La Silla is also the most southern ESO observatory site. The minimum value of PWV measured in this campaign was 2.93 mm, corresponding to an AP. The maximum value of PWV measured was 9.62 mm, corresponding to an AP with the additional presence of cirrus clouds. As shown in Table 5, the most typical synoptic pattern in this campaign was AP, occuring ~58% of the time.

The campaign performed at APEX observatory was carried out in the month of July (winter season). Conditions were very dry the first few days but the presence of CL over APEX contributed to high values of PWV. In this condition, the maximum PWV measured was 4.79 mm. The minimum PWV was 0.23 mm, with the presence of AP/JS without the presence of cirrus clouds. The most typical synoptic pattern during this period was AP/JS because was 50% of the radiosonde campaign (Table 5).

The last two campaigns were conducted at the Paranal site, the first was during the winter season and the second was during the latter part of the spring season. In both campaigns, the mean PWV was >1.5 mm, but the campaign during the winter season had occurances of PWV <1 mm. In that campaign the minimum value of PWV was 0.37 mm, during the influence of AP/JS without cirrus clouds. The maximum value of PWV was 3.72 mm due of the presence of HT/JS.

Table 5. Statistics of the synoptic patterns present during the radiosonde campaigns.

Synoptic Pattern	**Observatory**			
	La Silla	APEX	Paranal (1)	Paranal (2)
AP	58%	25%	17%	10%
CL	6%	20%	-	-
HT	12%	-	-	7%
AW	-	-	-	21%
AP/JS	12%	50%	48%	21%
CL/JS	6%	5%	13%	-
HT/AP	6%	-	-	-
HT/JS	-	-	22%	10%
AW/JS	-	-	-	21%
AP/AW/JS	-	-	-	10%

6. CONCLUSION

The evaluation of the data analyzed and forecasts made by the WRF model show that APEX observatory has the lowest errors in the values of PWV. With respect to the vertical profiles, the simulation is good at predicting the atmospheric parameters. The third campaign conducted at the Paranal site was the second to obtain good results, but the errors in both the analysis and forecast were >1.5 mm. The lowest error values analysed by the model were the 75% of the data that had an error <1.86 mm.

As we can see in the times series of analyzed and forecasted data by the WRF model to La Silla and Paranal site, has an error but they present the same tendency. This is because the place were performed the launchs of the radiosondes are not the same coordinated used on the model. The difference in distance can be between 1 Km (La Silla) and 500 m (Paranal). But in APEX this the launchs were made nest to the antenna, that why the error is more lowest.

The fourth campaign, again at Paranal, had PWV values larger than the third campaign. One possible difference is that during the winter season, the atmosphere in the north of Chile is more stable, with the presence of the anticyclone predominance (AP) occurring for a significant amount of time. While, during the spring season, the north of Chile develops more instability and received a higher contribution of water vapor originating from the Amazon (source of the Altiplanic Winter).

With respect to the evaluation of PWV extracted from GOES 12 images, the results are not good, the best were the values obtained were giving a correlation on GOES/FNL of about 0.56. The methodology used to calculated the PWV from the GOES-12 was develop only for the characteristics of APEX. Future work is calculated the value of PWV to La Silla and Paranal sites.

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REFERENCES

[1] Naylor, D.A., Phillips R.R., Di Francesco J., Bourke T.L., Querel R.R. and Jones S.C.," IRMA as a Potential Phase Correction Instrument: Results fro the SMA Test Campaign", Int J. of Infrared ans Millimeter waves, DOI 10.1007/210762-008-9421-2 (2008)

[2] Åkerberg, J., “State-of-the-art radiosonde telemetry, Eighth Symposium on Integrated Observing ans Assimilation Systems for Atmosphere, Oceans and Land Surface”, American Meteorological Society, (2004)

[3] Skamarock, W.C.,Klemp, J. B.,Dudhia, J.,Gill,D. O.,Barker D. M.,Wang, W. and Powers, J. G., "A Description of the Advanced Research WRF Version 2", NCAR Technical Note NCAR/TN-468+STR, (2005).

[4] Soden, B. J., Turner, D., Lesht, B. M. and Miloshevich, L. M. "An analysis of satellite, radiosonde, and lidar observation of upper tropospheric water vapor the Atmospheric Radiation Measurement Program", J. Geophysical Research. 109, D04105 (2004).

[5] Soden, B. J., and Bretherton, F. P., "Upper tropospheric relative humidity from the GOES 6.7 mm Channel: Method and climatology from July 1987", J. Geophys. Res., 98, 16, 669-688 (1993).

[6] Soden, B. J., and Lanzante, J. R., "An assessment of satellite and radiosonde climatologies of upper tropospheric water vapor", J. Climate, 9, 1235-1250 (1996).

[7] Erasmus, D.A., and Sarazin, M., "In Forecasting Precipitable Water Vapor and Cirrus Cloud Cover For Astronomical Observatories: Satellite image processing guided by synoptic model dissemination data", Proc SPIE 4168-17, (2000).

[8] Erasmus, D.A., and Sarazin, M., "Utilizing satellite data for evaluation and forecasting applications at astronomical site",Proc IAU SITE, (2000).

[9] Weinreb, P., Johnson, J. X. and Han, D., "Conversion of GVAR Infrared Data to Scene Radiance or Temperature", NOAA Technical Memorandum. NOAA NESDIS Office of Satellite Operations (2009).

[10] Cuevas, O., Chacón, A. and Curé, M., "Analysis of local meteorological conditions in Macón using the MM5 modeling system", Proc SPIE 7016, pp 701620-701620-12 (2008).

[11] http://dss.ucar.edu/datasets/ds083.2/